PB82-154865

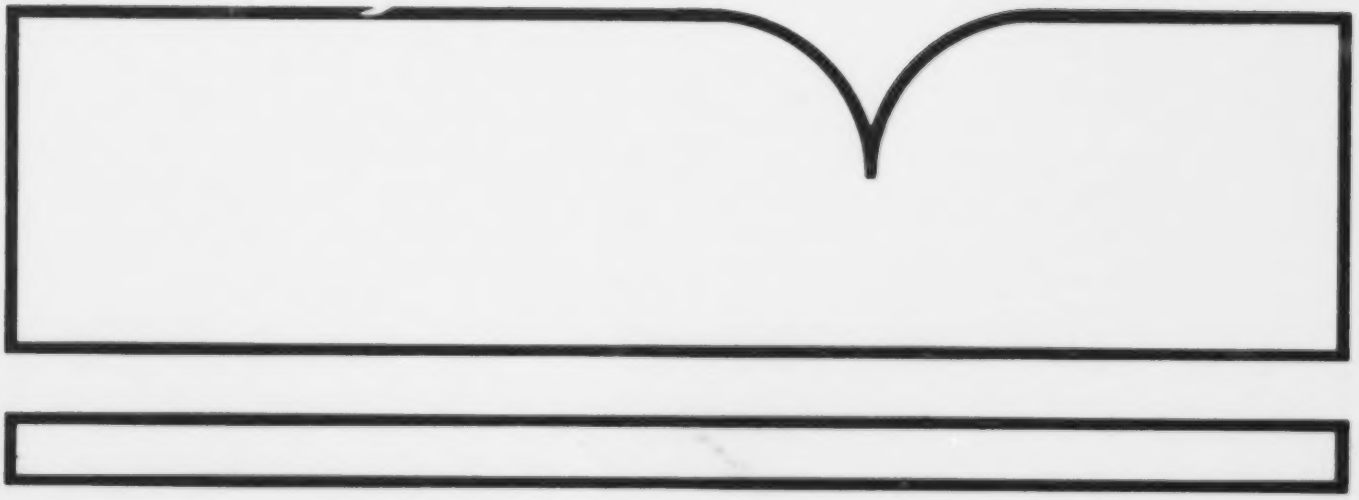
A Sensitive NMR Thermometer for Multinuclei FT NMR

Florida State Univ., Tallahassee

Prepared for

Health Effects Research Lab.
Research Triangle Park, NC

6 Aug 79



U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

XX-81-063

1. REPORT NO.	2.	3.
EPA-600/J-80-375	JOURNAL ARTICLE	PB82-154865

4. TITLE AND SUBTITLE	5. REPORT DATE
A Sensitive NMR Thermometer for Multinuclei FT NMR	January 1982
	6. PERFORMING ORGANIZATION CODE 025106

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
George C. Levy, J. Terry Bailey, David A. Wright	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Department of Chemistry The Florida State University Tallahassee, Flordia 32306	CCAE1A
	11. CONTRACT/GRANT NO. R804916

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Office of Research and Development (RTP,NC) Health Effects Research Laboratory US Environmental Protection Agency Research Triangle Park, NC 27711	14. SPONSORING AGENCY CODE EPA-600/11

15. SUPPLEMENTARY NOTES

Published In: Journal of Magnetic Resonance 37:353-356, 1980

16. ABSTRACT

A pernicious problem in multinuclei FT NMR is accurate measurement of sample temperature. This arises from several factors including widespread use of high-power decoupling, large sample tubes (with potentially large temperature gradients across the sample volume), and lack of suitable compounds having temperature-dependent shielding characteristics. The use of proton shieldings is generally precluded as a result of ^1H decoupling.

Use of thermocouples or thermistors to monitor sample temperature involves either measurement of flow gas temperature (which may not be the same as the sample temperature) or insertion of the device into the sample. Although the latter practice may give an accurate temperature reading at any one point in the sample, it is not sensitive to gradients in temperature. Stopping an experiment and placing one of these devices in a sample necessarily perturbs the temperature of the sample. In addition, there is evidence of thermocouple thermometry errors resulting from large magnetic fields.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	5
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

Form 2220-1 (9-73)

EPA-600/J-80-375
Journal Article

JOURNAL OF MAGNETIC RESONANCE **37**, 353–356 (1980)

A Sensitive NMR Thermometer for Multinuclei FT NMR

A pernicious problem in multinuclei FT NMR is accurate measurement of sample temperature (*1*). This arises from several factors including widespread use of high-power decoupling, large sample tubes (with potentially large temperature gradients across the sample volume), and lack of suitable compounds having temperature-dependent shielding characteristics. The use of proton shieldings is generally precluded as a result of ^{1}H decoupling.

The deuterium lock channel, present on most modern commercial spectrometers, may be used to probe sample temperature (*2*). However, the method is limited by the small temperature coefficient observed for ^{2}H shielding, about 0.01 ppm per degree in the case of a mixture of deuterated and protio-methanol and water (*2*).

Several ^{13}C thermometers have been proposed (*3–5*) for use in ^{13}C spectroscopy. These methods have accuracies/sensitivities ranging from a few degrees to perhaps $\pm 1°C$ under carefully controlled conditions. Recently an ^{19}F NMR thermometer suitable for low-temperature experiments was introduced (*6*).

Use of thermocouples or thermistors to monitor sample temperature involves either measurement of flow gas temperature (which may not be the same as the sample temperature) or insertion of the device into the sample. Although the latter practice may give an accurate temperature reading at any one point in the sample, it is not sensitive to gradients in temperature. Stopping an experiment and placing one of these devices in a sample necessarily perturbs the temperature of the sample. In addition, there is evidence of thermocouple thermometry errors resulting from large magnetic fields (*7*).

We now propose a high-sensitivity NMR thermometer for use in broadband design NMR probes or dedicated ^{13}C probes. Broadband design probes are already available on many commercial spectrometers; their future use will undoubtedly become ubiquitous. In this method we use the high temperature dependence (1.5 to 3 ppm/°C!) of ^{59}Co resonances in Co^{3+} compounds. The unusually large temperature coefficient for ^{59}Co shielding was noted early (*8*); the widespread applicability of a ^{59}Co thermometer awaited modern probe technology.

One advantage of a ^{59}Co NMR thermometer is the fact that ^{59}Co is a nuclide of very high sensitivity (1572 times as sensitive as ^{13}C), enabling dilute solutions to be used (*9*). If the solvent is a deuterated one, the same sample may be used for field/frequency control. Capillaries and external annular rings containing cobalt samples may be used individually, or together, to monitor temperature in the center and at the edge of sample tubes. Furthermore, the resonance frequence of ^{59}Co occurs in a convenient range, allowing for alternate detection schemes. For temperature measurement in samples where ^{13}C spectra are being obtained, the close proximity of the resonance frequencies ($\Delta \approx 1$ MHz at typical magnetic fields) combined with high signal strength allows detection of ^{59}Co through the ^{13}C channel with *no* retuning of the probe.

Another advantage is that aqueous and organic soluble species are available, allowing for a choice of solvents. The most suitable compounds seem to be $K_3Co(CN)_6$ for aqueous solutions and $Co(acac)_3$ for organic solvents (required for temperatures below 0°C). In addition, the ^{59}Co signal for the proposed aqueous ^{59}Co thermometer is sufficiently sensitive to monitor small temperature gradients across NMR samples (important for large sample tubes), and decoupling and sample spinning may be continued during temperature measurement.

One disadvantage of ^{59}Co as a temperature reference is its sensitivity to pressure (~0.1 ppm/atm) (*10*), concentration (~3 ppm between saturated solutions and infinite dilution), and solvent (total range, ~20 ppm). The resonance frequency also may be nonlinear with respect to magnetic field (less than 2.5 Hz/T) (*11*). Precautions must be taken to maintain reasonable constancy of these variables.

Thus far we have investigated two suitable ^{59}Co species: $K_3Co(CN)_6$ in D_2O and cobalt tris(acetylacetonate), $Co(acac)_3$ in $CDCl_3$ (both 0.1 *M*). The high symmetry of the hexacyano complex produces a long ^{59}Co T_1 (155 msec at 3.5 T and 29°C), giving a linewidth of about 2 Hz. $Co(acac)_3$ has a linewidth of about 80 Hz at this temperature. $Co(NH_3)_6Cl_3$ was also investigated but was found to be unsuitable. Although it is symmetric and shows a ^{59}Co T_1 of approximately 44 msec at 25°C, coupling to the rapidly relaxing nitrogens broadens the resonance to 540 Hz.

In these experiments 25-mm tubes were utilized with the cobalt compound contained in a coaxial 8-mm tube. The outer tube contained a 50 : 50 (v/v) mixture of acetone-d_6 and carbon tetrachloride as a secondary temperature reference (*12*). The absolute cobalt frequency at 0°C was determined for use as the reference in chemical shift calculations. Then a temperature vs shift calibration chart was constructed. Such a plot for $Co(acac)_3$ in $CDCl_3$ is shown in Fig. 1. A least-squares fit of the line results in an equation relating temperature to the chemical shift between the reference at

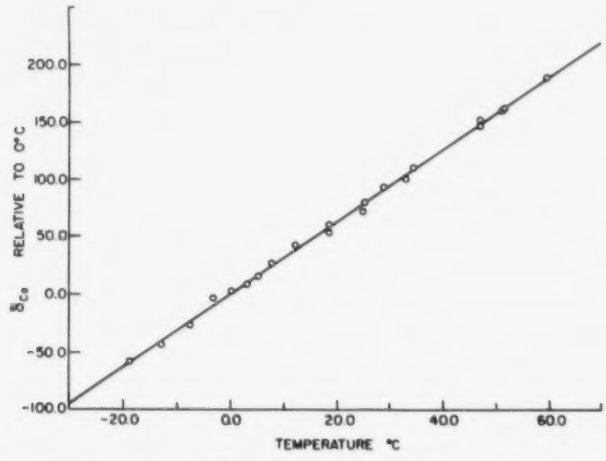


FIG. 1. Temperature dependence of $^{59}Co(acac)_3$ chemical shift, (in ppm) referenced to absolute ^{59}Co frequency at 0°C.

0°C and any other temperature; these are given in Eq. [1] for $K_3Co(CN)_6$ and Eq. [2] for $Co(acac)_3$.

$$T_{°C} = \delta Co/1.504 \quad [1]$$

$$T_{°C} = \delta Co/3.153. \quad [2]$$

The correlation coefficients for these plots were 0.998 and 0.999, respectively. Measurements covered temperature ranges of approximately −2 to 67°C for $K_3Co(CN)_6$ and −20 to 60°C for $Co(acac)_3$. In order to apply these equations to any instrument, only the reference frequency at 0°C must be found. For example, at 3.52 T and 27.1°C, the ^{13}C signal from TMS in CCl_4 is found at 37,708,184 Hz, and the ^{59}Co signal from $K_3Co(CN)_6$ in D_2O at this temperature is found at 36,027,992 Hz.

The advantage of using the ^{59}Co lineshape of $K_3Co(CN)_6$ as a monitor of temperature gradients is shown experimentally for 25-mm sample tubes. In this case the cobalt solution occupies the whole sample volume.

For a sample which has been completely equilibrated at ambient probe temperature (26.3°C) thermal gradients are expected to be minimized. The ^{59}Co resonance of $K_3Co(CN)_6$ in D_2O/H_2O after equilibration confirms this by showing essentially no half-height line broadening relative to the ^2H line. However, there is some baseline distortion (broadening) of the ^{59}Co resonance below the 20% height of the line (~15 Hz) showing some thermal inhomogeneity. This situation is greatly magnified when the sample is heated, as may be seen in Fig. 2, where trace A shows the ^{59}Co resonance observed when the sample is nominally at 41°C. Since a check of the D_2O resonance shows the H_0 field to be homogeneous, the lineshape shown in B reflects in some way a temperature gradient of about 2° across the sample. These effects were observed only when the sample was spinning. Presumably centrifugal forces short-circuit normal diffusion currents and prevent complete thermal mixing.

Since the resonance shifts downfield (to the left) with increasing temperature, the most intense part of the resonance (deshielded) probably corresponds to the end of the tube nearest the heater. The response to a 180° pulse (trace B) shows that the nuclei near the ends of the 25-mm sample tube do not experience the same H_1 field

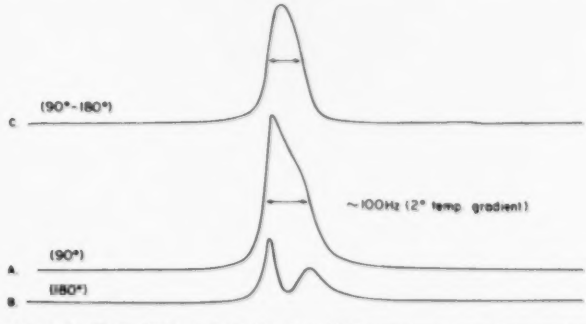


FIG. 2. ^{59}Co signals for $K_3Co(CN)_6$ in D_2O/H_2O at 41°C showing a large temperature gradient in the 25-mm sample tube. (A) 90° pulse, (B) 180° pulse, (C) difference spectrum of A–B. Plot width is 1250 Hz.

strengths as the nuclei in the center. The difference spectrum (between A and B) is shown in C; this is a measure of H_1 intensity across the sample.

ACKNOWLEDGMENT

We gratefully acknowledge financial support from the US Environmental Protection Agency.

REFERENCES

1. F. A. L. ANET, *in* "Topics in Carbon-13 NMR Spectroscopy," Vol. 3, Chap. 1, 1979.
2. I. Y. SLONIM, B. M. ARSHAVA, AND V. N. KLYUCHNIKOV, *Zh. Fiz. Khim.* **50,** 277 (1976) [*Russ. J. Phys. Chem.* **50,** No. 1, (1976)].
3. D. R. VIDRINE AND P. E. PETERSON, *Anal. Chem.* **48,** 1301 (1976).
4. S. COMBRISSON AND T. PRANGE, *J. Magn. Reson.* **19,** 108 (1975).
5. H. J. SCHNEIDER, W. FREITAY, AND M. SCHOMMER, *J. Magn. Reson.* **18,** 393 (1975).
6. J. BORNAIS AND S. BROWNSTEIN, *J. Magn. Reson.* **29,** 207 (1978).
7. T. E. KOLLIE, R. L. ANDERSON, J. L. HORTON, AND M. J. ROBERTS, *Rev. Sci. Instrum.* **48,** 501 (1977).
8. W. G. PROCTOR AND F. C. YU, *Phys. Rev.* **81,** 20 (1951).
9. R. K. HARRIS AND B. E. MANN (Eds.), "NMR and the Periodic Table," p. 225, Academic Press, New York/London, 1978.
10. G. B. BENEDEK, R. ENGLEMEN, AND J. A. ARMSTRONG, *J. Chem. Phys.* **39,** 659 (1979).
11. M. R. BENDALL AND D. M. DODDRELL, *J. Magn. Reson.* **33,** 659, (1979).
12. J. J. LED AND S. B. PETERSON, *J. Magn. Reson.* **32,** 1 (1978).

GEORGE C. LEVY*
J. TERRY BAILEY
DAVID A. WRIGHT†

Department of Chemistry
The Florida State University
Tallahassee, Florida 32306

Received August 6, 1979

* Camille and Henry Dreyfus Teacher–Scholar.
† Current address: Department of Chemistry, University of Illinois, Champaign–Urbana, Ill. 61801.